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A Hierarchical Analysis of Bridge Decision Makers

The Role of New Technology Adoption in the Timber Bridge Market: Special Project Fiscal Year 1992

PREFACE

This publication is a technology transfer effort by the USDA Forest Service, Timber Bridge Information Resource Center, in cooperation with the Center for Forest Products Marketing, Department of Wood Science and Forest Products, at Virginia Polytechnic Institute and State University, under a grant from the USDA Forest Service.

This publication examines the process used to characterize the bridge material selection by design engineers and local highway officials. The Analytical Hierarchy Process is used to quantify factors that affect decision criteria and materials selected. Strategies are recommended for promoting timber as a bridge material.

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Other publications in this five-part series are:

- **Factors Influencing the Adoption of Timber Bridges (Literature Review), NA-TP-02-95 (Part I)**
- **A Perceptional Investigation into the Adoption of Timber Bridges, NA-TP-03-95 (Part II)**
- **Marketing Practices in the Timber Bridge Industry: 1993, NA-TP-05-95 (Part IV)**
- **A Strategic Evaluation of Factors Affecting the Adoption of Timber Bridges, NA-TP-06-95 (Part V)**

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Timber Bridge Information Resource Center

TECHNOLOGY
TRANSFER

The Role of New Technology Adoption in the Timber Bridge Market: Special Project Fiscal Year 1992

A Hierarchical Analysis of Bridge Decision Makers

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ABSTRACT

Bridge design engineers and local highway officials make bridge replacement decisions across the United States. The Analytical Hierarchy Process was used to characterize the bridge material selection decision of these individuals. State Department of Transportation engineers, private consulting engineers, and local highway officials were personally interviewed in Mississippi, Virginia, Washington, and Wisconsin to identify how important factors determine their choice of a bridge material. The Analytical Hierarchy Process allowed us to quantify this subjective material selection decision for different groups of decision makers. Based on the importance of various decision criteria and how well the material alternatives (steel, reinforced concrete, prestressed concrete, and timber) meet them, strategies are recommended for those promoting timber as a bridge material.

INTRODUCTION

The disciplines of *Management* and *Marketing* have evolved into separate sciences over the years. *Management* is organization driven, wherein the effective manager must determine the purpose and direction of the organization, foster and manage change, and conduct operations so that the organization and its people function efficiently and effectively (Levitt 1991). Levitt states that managers make decisions. Decisions deal with choices. Choices involve alternatives, which include prospects for making, avoiding, resisting, and creating change. Drucker (1983) states that effective management requires precise analysis, rigorous allocation of resources, and timely decision making. Managers are accountable to stockholders, financial backers, employees, and customers, so choices must be not only the *best*, but also justifiable.

Marketing has been called a philosophy. It is a total system of business activities which is designed to determine customers' needs and desires, to plan and develop products to meet those needs and desires, and to determine the best way to price, promote, distribute, and service the customer (Stanton 1978). This is often referred to as the *marketing concept*. Sinclair (1992) states that a marketing-oriented firm designs its products and service offerings to meet customer needs at a profit. Marketing is the income-generating activity of the firm, the process by which the organization reaches out to its customers, and the means by which customers reach in to the firm.

Management often utilizes decision-analysis tools to more effectively run their organizations. Marketing departments rely upon research methods involving customer surveys, purchasing activities, or demographics to understand and meet customer needs. Yet, as Drucker (1984, p. 1) states, *"Marketing is so basic it cannot be considered a separate function...It is the whole business seen from the point of view of its final result, the customer."* Following on this idea, this study crosses the boundary between modern management decision analysis and the marketing concept. This study examines how particular criteria affect material-selection decisions for rural bridges. Quantification of this decision process should allow manufacturers of bridge materials to improve their ability to meet design engineers' and highway officials' needs.

Timber Bridges

Highway officials and engineers across the United States have been asked to reevaluate their position on the use of timber as a bridge material. In 1989, the Timber Bridge Initiative (TBI) began an extensive promotion and training program (TBI 1990) to inform and educate bridge engineers and highway officials concerning the benefits of the modern timber bridge. It is believed that with an increase in the use of timber, local economies can be stimulated and the rural infrastructure rebuilt.

Since its inception, the TBI has sponsored the construction of over 272 modern timber bridges in 48 states and assisted in 17 million dollars of research, educational, and bridge-supported activities (USDA 1993). However, the long-term viability of timber bridges will depend not only upon this *technology push*, but the competitiveness and acceptance in the marketplace, the *market pull.*

Unfortunately, bridge engineers across the United States often have negative perceptions of timber as a bridge material. Studies by Clapp (1990) and Luppold (1990) have confirmed that engineers are not ready to place timber in the same bridge material classification as prestressed concrete, steel, or reinforced concrete. Engineers have stated that timber is short lived, difficult to inspect, expensive, high in maintenance, and low in strength. Yet, numerous factors are known to affect the performance of bridge materials. Ritter (1990) states that poor design, poor construction, and poor management practices lead to performance problems with timber in bridges. Yet, little is known about non-structural factors influencing the bridge selection process and their effect upon the final decision.

The choice of a material is the most important decision bridge designers make, and it has long-term consequences for the owner of the structure (Johnson 1990). Bridge material selection is a complex decision, with many individuals involved, and many factors of bridge design, use, and maintenance to be considered. It is not uncommon to have state Department of Transportation (DOT) officials, private consultants, and local officials work together on a bridge replacement decision. Each of these groups may have their own preferences concerning bridge materials. Often a consensus is necessary to determine the best material to use at a given location.

Ellen et al. (1991) indicate that humans or organizations tend to avoid change by favoring the current situation or status quo, unless an alternative is presented which is excessively attractive or very pressuring. Decision making tends to be based upon previous solutions and past successes, unless they are no longer viable. With over 93% of recent bridges being built out of prestressed concrete, reinforced concrete, or steel (FHWA 1992), decision makers appear reluctant to try timber in rural bridge replacement.

One of the primary reasons for new product failure is inadequate market research. Three studies undertaken over 25 years reveal that inadequate market analysis remains the primary cause of new product failure (National Industrial Conference Board 1964, Hopkins and Bailey 1971, Hopkins 1980). Cooper (1988) states that the list of reasons for failure includes lack of thoroughness in identifying real needs of the customer and competitors' reactions in the marketplace. The modern timber bridge can be classified as a new product. To effectively market this new product, the timber bridge industry must understand the current bridge material selection process. Once this decision process has been explained, customers' needs can be effectively addressed.

Scott and Keiser (1984) state that much of the research that is done in industrial markets to identify and evaluate new opportunities is quantitative and unstructured. We demonstrate in this study that qualitative and structured analysis of decision makers can be a useful tool for understanding customers and their perceptions. We develop a behavioral model of bridge material selection for several states and for several levels of decision makers.

In this study, important non-structural factors (criteria) in the bridge material selection process were solicited from highway officials in 28 states. We used the highest rated six factors in the Analytic Hierarchy Process (AHP) to determine the placement preference for steel, prestressed concrete, reinforced concrete, and timber by bridge design engineers and highway officials in four selected states. The AHP model helped us analyze how important decision criteria directly influence the overall bridge material decision. From this developed recommendations for marketing strategies that can be used to increase the knowledge and application of timber as a bridge material.

BACKGROUND

The Bridge Decision Problem

Many factors are known to affect the choice of a bridge material. *Physical characteristics or site-specific factors* include: roadway alignment, length of clear span, clearance above waterway, hydraulic capacity requirements, and required loading capabilities. There are numerous *non-structural characteristics* of bridge materials such as initial cost and maintenance (Table 1) that may also influence this decision. These are the areas which manufacturers can address in trying to influence the choice of bridge material by design engineers. The four principal bridge materials, which, according to the FHWA (1992) represent 99% of the bridges built in the United States since 1982, are prestressed concrete, steel, timber, and reinforced concrete.

The Analytical Hierarchy Process (AHP)

Although various techniques exist for modeling decision making, the AHP was chosen for this study. The AHP can be used as both a behavioral and normative model of decision making. That is, it can be used to model an existing decision-making process or to prescribe what decision one should make in a particular situation. It has the advantage of utilizing qualitative, as well as quantitative data. Qualitative data is important in this research because of the necessity to determine the underlying (i.e., subjective) reasons for the decline in timber bridges in the United States and the slow rate of adoption of current timber bridge technology. Only by asking the people who make the decisions can appropriate answers be discovered and strategies formulated to change the current patterns. Qualitative inquiry cultivates the most useful of all human capacities—the capacity to learn from others (Patton 1990).

The Analytic Hierarchy Process, developed by Thomas Saaty in the early 1970s, allows us to quantify and aggregate subjective opinions. Saaty (1980) states that the practice of decision making is concerned with weighing alternatives which fulfill a set of desired objectives. This multicriterion,

multiperson model structures the decision process into a hierarchy. Through a set of pair wise comparisons at each level of the hierarchy, a matrix can be developed, where the entities indicate the strength with which one element dominates another with respect to a given criterion.

Harker and Vargas (1987) indicate that there are three principles used in the AHP for problem solving: (1) *decomposition* - structures the elements of the problem into a hierarchy, (2) *comparative judgments* - generates a matrix of pair wise comparisons of all elements in a level with respect to each related element in the level immediately above it where the principal right eigenvector of the matrix provides ratio-scaled priority ratings for the set of elements compared, and (3) *Synthesis of priorities* - generates the global or composite priority of the elements at the lowest level of the hierarchy, i.e., the alternatives. The four basic axioms that the AHP is based upon is summarized by Harker (1989) as follows:

Axiom 1. Given any two alternatives (or sub-criteria) i and j out of the set of alternatives A, the decision maker is able to provide a pair wise comparison a_{ij} of these alternatives under any criterion c from the set of criteria C on a ratio scale which is reciprocal; i.e., $a_{ji} = 1 / a_{ij}$ for all i, j, & A.

Axiom 2. When comparing any two elements i, j, & A, the decision maker never judges one to be infinitely better than another under any criterion c & C; i.e., $a_{ij} \neq \infty$ for all i, j, & A.

Axiom 3. One can formulate the decision process as a hierarchy.

Axiom 4. All criteria and alternatives which impact the given decision problem are represented by a hierarchy. That is, all the decision-maker's intuition must be represented, or excluded, in terms of criteria and alternatives in the structure and be assigned priorities which are compatible with the intuition.

METHODS

Data Collection

Primary data

A disguised mail questionnaire was sent to over 1300 decision makers to collect primary data concerning important *non-structural factors* (criteria) that influence the bridge material decision. Participants were asked to assume the bridge site allowed for equal choice of material. This was meant to eliminate *physical or site-specific characteristics* that may influence the material choice.

Decision makers in 28 states were classified into five distinct geographic regions (Table 2) and three decision-making groups. The groups were state DOT engineers, private consulting engineers, and local highway officials. Survey respondents were asked to rate 23 non-structural criteria in the selection of a bridge material (Table 1). The questionnaire used rating scales from 1 to 7 to measure the importance of the criteria. Criteria were selected by an extensive secondary literature search, discussions with civil engineers across the United States, and interviews with University personnel.

A pretest was conducted with bridge engineers in various decision groups in Virginia, Wisconsin, and Minnesota. After minor clarification of question wording, the questionnaire was sent out in April 1993. No correspondence stated that the study was being conducted by the Department of Wood Science at Virginia Tech since it was believed this may bias some results or have an undesirable effect on the response rate. After two mailings, a total of 848 surveys were returned, 751 of which were usable, resulting in an adjusted response rate of 61%.

Non-Response - In order to test for non-response bias, 50 non-respondents were contacted by telephone and asked to answer selected questions. These individuals represented the three primary decision-making groups. They were asked questions concerning material preference, ratings of important bridge material factors, timber design education, and job duties. Multivariate Analysis of Variance (MANOVA) was utilized to determine if significant differences existed between respondents and non-respondents on the selected parameters. In no case could the hypothesis of no difference between respondents and non-respondents be rejected ($\alpha = .05$).

Personal Interviews

During August, September, and October of 1993, semi-structured interviews were conducted with 73 design engineers and highway officials in four selected states: Mississippi, Virginia, Washington, and Wisconsin. These states were chosen based on their geographic differences, timber resources, and bridge decision-making protocol. Participating in this were state department of transportation engineers involved in preliminary design or local bridge maintenance/replacement decisions, private consulting engineers involved with local bridge design, and county highway officials. Interviews with county officials and private consultants were limited to one engineer per location.

Composite AHP models were developed for each group of decision makers in the four separate states (Figure 1). A questionnaire was designed for participants to use for completion of the AHP model. This questionnaire consisted of paired comparisons among the six highest ranked criteria involved in the decision process (Table 3) as determined by the initial survey. It also included comparisons among the different types of bridge material with respect to each criteria. A rating scale from 1 to 7, as recommended by Saaty (1980), was used for the paired comparisons. The Number 1 value indicated that compared factors were equal in importance and Number 7 indicated that one factor was extremely more important than another. This questionnaire was reviewed by qualified personnel at Virginia Tech and pretested with private consultants and state DOT engineers in Virginia.

Each decision maker made 51 paired comparisons to complete their individual AHP model. The computer program, Expert Choice (1992), assisted in development and analysis of the models. A lap-top computer was used to input the data to Expert Choice as each official responded to the questionnaire. This allowed immediate feedback to the decision maker on his/her preferences and overall choice of a bridge material. Individual results were then combined as geometric means to produce group decisions representing the separate decision-making groups in each state.

The balance of the interview was exploratory in nature. Responses were recorded for interpretation and analysis. Specific areas of interest included: bridge costs, best locations for timber bridges, concerns with timber as a bridge material, guidelines on timber use, amount of bridge work in state, best material for short span bridges, reasons the state doesn't use more timber in bridges, bidding processes within the state, and factors that would allow the state to use more timber bridges.

States

Mississippi - This state is located in the heart of the southern pine resource and is one of the states having the highest number of timber bridges (more than 3,500) (FHWA 1993). Design decision makers in Mississippi include state DOT and county engineers. The county engineer is a private consultant hired by the county board of supervisors for a 4-year term. This consultant sometimes serves as many as five different counties. All bridges utilizing Federal Highway bridge replacement funds or state funds must be designed by the county engineer. The Mississippi DOT, which administers funding and reviews bridge plans, is divided into two sections: (1) the secondary roads division which directs the local roads program and (2) the DOT which directs state and federal highway programs. Both divisions are strong supporters of standardized bridge plans, which at the time of the interviews did not include plans for timber. More than 70% of the nearly 12,000 state bridges fall under local/county jurisdiction (USDA 1989).

Virginia - This Mid-Atlantic state has a large eastern hardwood and southern pine timber resource base and is one of the states with the lowest number of timber bridges (less than 60) (FHWA 1993). The state DOT maintains more than 97% of the state's bridges. Virginia is divided into nine highway districts, with a chief bridge engineer directing maintenance and replacement activities within each district. Private consultants are used occasionally when the work load is too great for the district engineers to handle. Virginia utilizes standard bridge plans that do not include complete plans for timber bridges. Temporary structures and timber plank on steel stringers are the only standard type plans available.

Washington - Located in the Pacific-Northwest, Washington has a large softwood timber resource. Yet, only 600 of the state's nearly 7,000 bridges are timber. Three decision-making groups are involved in bridge replacement in Washington. The state DOT has a local program engineer who works with counties on bridge replacements, and a staff of engineers in the central office that design state and federal highway bridges. Private consulting engineers are often hired by counties to design their rural bridges. Each county in Washington is required to have a registered civil engineer on staff to oversee local highway maintenance. This engineer or his/her assistant will often design a rural bridge. Sixty-five percent of the state's bridges fall under local control. Washington utilizes standard plans; however, the only plans for timber are for temporary structures, such as detours.

Wisconsin - Located in the upper Midwest, Wisconsin is one of only five states that has shown an increase in timber bridges from 1986 to 1992 (FHWA 1992). Over 500 of the state's nearly 12,000 bridges are classified as timber. Three groups of decision makers are involved in design decisions in Wisconsin. The state Department of Transportation (DOT) is divided into eight highway districts, each with a bridge engineer that works with counties on maintenance and replacement. Private consultants are hired by counties to design rural bridges. County highway commissioners are re-

sponsible for maintenance of local, state, and Federal highways within their county boundaries. The county highway commissioner does not have to be an engineer, but the trend is to hire engineers in that position. The commissioner, in most cases, is appointed by the board of supervisors for a 2- or 4-year term. Wisconsin has standard bridge plans that do include plans for timber bridges.

RESULTS

The most important non-structural factors (criteria) rated by all decision-making groups across every region of the United States include: *expected life of material, material's past performance, maintenance requirements, resistance to natural deterioration, initial cost, and life-cycle cost* of material (Table 3). Six criteria were chosen because of their importance, statistical significance from the remaining factors ($p < .01$), and to keep the number of paired comparisons (51) for the respondents to a minimum. These decision criteria are areas in which timber manufacturers need to address their efforts to promote timber bridges more successfully. All six criteria were used in the models subsequently developed using the AHP.

To determine if the four selected states (Mississippi, Virginia, Washington, and Wisconsin) were representative of their respective geographic regions, a Multivariate Analysis of Variance (MANOVA) was run on the selected criteria between the individual state and its region. No significant difference (α=.05) between each state and its region on these six factors was apparent. Analysis of Variance was used to determine if the states differed from others in the respective regions based on perceptions of timber as a bridge material. Again, no statistical differences could be shown. These results indicate that each state is representative of the region in which it is located and should provide a good indicator of bridge decision making in that region.

The AHP for Wisconsin Counties

To demonstrate how an AHP model is developed, an example based on county decision makers in Wisconsin is provided. In August 1993, nine county highway commissioners/engineers agreed to participate in completing the paired comparison questionnaire. The counties were geographically dispersed across Wisconsin, and respondents were either county engineers or county highway commissioners. The purpose of the interview was explained and as the official filled out the questionnaire, the responses were entered into a personal computer using the program, Expert Choice. First, paired comparisons were made among the six important bridge criteria. Under each criteria, paired comparisons were made for preferences of bridge materials. Exploratory questions regarding bridge replacement decisions were discussed at that time. At the completion of the nine interviews, individual results were geometrically averaged, and one composite matrix was developed (Table 4) representing county decision makers in Wisconsin.

Calculation of a final priority vector for bridge material preference proceeds in the following way. First, the data in the bridge criteria matrix are normalized by column. Second, the values in each row are averaged to produce a vector of priorities for each bridge criterion (Table 5). Third, similar calculations are then repeated for each matrix of material preference under a given bridge criterion

(Tables 6-7). Upon completion of these steps, the final composite preference vector for bridge material is the matrix product of (1) the matrix composed of bridge material preference vectors and (2) the vector of bridge criteria (Figure 2). This is the choice of bridge material for the decision maker (in this case, county highway commissioners/engineers in Wisconsin) based upon the criteria measured (Figure 3).

This process was repeated with engineers and highway officials in the four selected states. Composite models were developed for each group in each state. Overall material decisions were calculated for each decision maker by state (Figure 4). Expert Choice also calculates an inconsistency ratio, which is a measure of how consistent a respondent is with the paired comparisons. That is, for comparisons among entities A, B, and C, the preference of A over C should equal the product of the preference of A over B and the preference of B over C, for the judgments to be consistent. Saaty (1980) states that an inconsistency ratio of less than 0.1 is excellent. Nevertheless, some inconsistency is inherent in most decision processes and should not necessarily be eliminated. The inconsistency ratios for aggregate responses of these decision-maker groups were all much less than 0.1. Table 8 summarizes the results of each state's models.

Individual decision models can be combined arithmetically to perform statistical analysis (Saaty 1993). To determine if differences existed between states or decision-making groups, non-parametric statistical procedures were utilized. Non-parametric procedures are recommended when sample size is small or the distribution of the population from which the data is obtained is uncertain (Hollander and Wolfe 1973). The importance of the six major criteria in the bridge decision are quite uniform across decision-making groups and between states (Table 9). Only for the criteria of *maintenance* did significant differences ($\propto < .05$) exist between the four states. This agrees with earlier findings by the authors that major criteria are similar by groups and regions.

Among the three major decision groups (DOT, private engineers, and local officials) aggregated across the four states, differences existed in the choices of steel and timber. Among the four states and the three decision groups, only reinforced concrete was not statistically different. In the states of Virginia and Wisconsin, differences existed between decision makers' preferences for timber. Both prestressed concrete and reinforced concrete were deemed to have different preferences across decision groups in Mississippi. Only in Washington were the preferences for bridge materials not statistically different by decision group. These results indicate that even though decision criteria are viewed similarly, the extent to which various bridge materials are perceived as meeting those criteria varies between states and between decision-making groups.

Sensitivity analysis was run on each model's bridge decision criteria to determine if increasing efforts in one or more areas would affect the bridge decision. Department of Transportation engineers favored prestressed concrete. This may be attributed to their exposure to state and federal highway bridges and a lack of familiarity with timber design. Private consultants and county officials favored prestressed and reinforced concrete for rural bridges.

In Mississippi, only if *initial cost* became extremely important would county engineers consider using timber instead of steel in their decisions. No changes would affect the Mississippi DOT engineers' decisions concerning timber. Virginia private consultants would choose timber above all other materials if *initial cost* became very important. Nothing would affect the decision of DOT

engineers in Virginia. In Washington, as *initial cost* became more important, local engineers and private consultants favored timber over steel, but never over concrete. Again, no changes would affect the decision of Washington DOT engineers. Wisconsin local engineers would prefer timber as *initial cost* became very important, and DOT engineers favored timber over steel when *maintenance* became increasingly important. Nothing affected Wisconsin private consultants' decision.

CONCLUSIONS

Decision-making applications of this research indicate that the Analytic Hierarchy Process can be utilized in a group situation to assist highway officials in their choice of a bridge material. This model reflects the current bridge situation in the United States, with prestressed and reinforced concrete being the major bridge material chosen over seventy percent of the time by highway officials.

Decision makers are in agreement about criteria that are important in the design decision from the list provided. Across the United States, these individuals rated the most important criteria similarly by region and decision group. *Maintenance requirements, initial cost, and past performance* were the most influential criteria in choosing a bridge material. However, these criteria, when applied to the AHP decision models, influenced the choice of bridge material differently. Nevertheless, prestressed concrete and reinforced concrete were the materials of choice by every group in each state.

These results indicate that *initial cost* may be a competitive advantage for timber in bridge design. However, timber is rated so low, based upon the other five criteria, that it will very seldom be chosen as a rural bridge material. As little can be done with the criteria of *past performance* of a bridge material, educational efforts are needed emphasizing that modern designed timber bridges are not the same as timber bridges built 40 to 50 years ago. Modern prestressed composites of steel and timber can perform as well, if not better, than other materials. In addressing the criteria of *maintenance*, modern composites of steel and wood should reduce deflection and movement in timber bridges, which may have caused many of the past problems. *Resistance to natural deterioration* can be improved by building structures with water-shedding joints, good preservative treatments, and waterproof surfaces. Stressed-type timber bridge systems should reduce the amount of water movement between wood members. Realistic comparisons of all bridge materials need to be made based on past design and construction practices. Concrete and steel structures may be performing better, because more of them have been built to modern standards than timber. *Life span and life-cycle cost* will both improve as timber lasts longer and becomes more competitive in the marketplace.

During interviews, questions were also asked about the problems with timber. In Mississippi, Virginia, and Washington a primary concern was life span. Engineers in each state indicated that treated timber is being replaced after 25 to 30 years in service. Initial cost of timber was a factor in most states. Timber is not perceived as cost competitive. Cost of timber, therefore, cannot influence the decision over other bridge materials. Because timber decays from the inside to the outside, inspection is more difficult for untrained engineers. This also increases the risk of using timber in bridge design as perceived by the highway official. The maintenance requirements of timber com-

pared to the other materials were seen as a deterrent to its use. Environmental concerns with wood preservatives and the timber resource supply were raised by Washington and Mississippi highway officials.

With state DOT engineers controlling the allocation of Federal highway funds, efforts must be made to convince the opinion leaders in this group that timber is a viable bridge material. Since this group chose timber the least in the bridge decision, every effort is needed to demonstrate the attributes of timber used in modern designs for rural bridges. To improve timber's perception by engineers, manufacturers need to address timber's short *life span and maintenance* requirements in a bridge situation.

Marketing applications of this work indicate that timber manufacturers may need to address other criteria besides those measured in this study to increase timber's market share. Other important bridge criteria that timber may compete on include *ease of repair, time of traffic interruption, resistance to deicing chemicals, and aesthetics*. Rural roads with county control offer the greatest opportunity for timber use, since individuals responsible for making these bridge decisions choose timber more often than DOT engineers. Manufacturers may want to look at other areas in which timber may be successful. Railroads, footbridges, light traffic bridges, and scenic covered bridges may offer further opportunities for timber in bridge applications.

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Table 1. Criteria in Determination of Bridge Material

Government research efforts	Standards specified by AASHTO	Material preference of local officials
Life-cycle cost of material	Past performance of the material in bridges	Availability of design information
Resistance to natural deterioration	Contractor's familiarity with material	Resistance to de-icing chemicals
Expected life of material	Bridge ownership (state, county, town)	Regular inspection requirements
Length of traffic interruption	Designers familiarity with material	Impact on local economy
Maintenance requirements	Industrial promotional efforts	Environmental considerations
Initial cost of material	Aesthetics	Ease of repair
Bridge loading variations	Daily traffic count	

Table 2. States Surveyed for Important Bridge Factors

West	South	Mid-Atlantic	Northeast	Midwest
California	Alabama	Kentucky	Maine	Indiana
Idaho	Arkansas	North Carolina	Massachusetts	Illinois
Montana	Florida	Tennessee	New York	Iowa
Oregon	Louisiana	Virginia	Pennsylvania	Michigan
Washington	Mississippi	West Virginia	Vermont	Minnesota
	Texas			Ohio
				Wisconsin

Table 3. Importance of Criteria in the Bridge Material Decision Process

	DECISION LEVEL (Mean Rating)			
Bridge Material Factor	Overall	Local	State	Private
Life span (1)	5.95	6.17	5.89	5.82
Past Performance (2)	5.92	5.93	5.98	5.83
Maintenance (3)	5.84	5.98	5.85	5.67
Natural Deterioration (4)	5.82	5.92	5.72	5.82
Initial Cost (5)	5.54	5.60	5.48	5.49
Life-cycle Cost (6)	5.51	5.62	5.45	5.51
Ease of repair (7)	5.25	5.41	5.19	5.16
AASHTO (8)	5.24	5.15	5.14	5.42
Time of Traffic (9)	5.08	4.98	5.26	5.01
Designer's Familiarity (10)	4.86	4.91	4.70	4.92
Design Information (11)	4.85	4.92	4.69	4.92
De-icing Chemicals (12)	4.84	4.38	5.03	5.05
Environmental Concerns (13)	4.66	4.74	4.68	4.53
Inspection Requirements (14)	4.65	4.68	4.66	4.62
Loading Variations (15)	4.56	5.05	4.34	4.38
Contractors Familiarity (16)	4.41	4.61	4.16	4.47
Daily Traffic (16)	4.41	4.58	4.41	4.24
Aesthetics (18)	4.34	4.20	4.27	4.51
Local Officials (19)	4.23	4.16	3.71	5.01
Local Economy (20)	4.11	4.59	3.80	4.07
Bridge Ownership (21)	3.98	4.07	3.72	4.24
Gov. Research (22)	3.82	3.76	3.85	3.74
Promotional Efforts (23)	2.81	2.88	2.76	2.76

Rating Scale: 1 (below average) to 7 (above average), average = 4

Table 4. Geometric Mean of Paired Comparisons of Bridge Factors as Rated by Nine Wisconsin Highway Officials

	Past perf	Life span	Maintence	Resistance	Initial	Life cycle
Past perf	1.0	1.10	.71	1.0	.53	1.0
Life span	.91	1.0	.71	1.4	.83	1.5
Maintence	1.4	1.4	1.0	1.7	1.3	1.6
Resistance	1.0	.71	.59	1.0	.67	.40
Initial	1.9	1.2	.77	1.3	1.0	1.2
Life cycle	1.0	.67	.63	2.5	.83	1.0
Total	7.21	6.08	4.41	8.90	5.16	6.70

Normalized Matrix of Paired Comparisons for Wisconsin Counties

Past perf	.139	.181	.161	.112	.103	.149
Life span	.126	.164	.161	.157	.161	.224
Maintence	.194	.230	.227	.191	.252	.239
Resistance	.139	.117	.134	.112	.130	.06
Initial	.264	.197	.175	.146	.194	.179
Life cycle	.139	.110	.143	.281	.161	.149

Table 5. Vector of Priorities for Wisconsin Counties

	Total of Normalized Row	Average of Normalized Row	Vector of Priorities
Past performance	.842	.842/6	.140
Life span	.993	.993/6	.166
Maintence	1.33	1.33/6	.222
Resistance	.692	.692/6	.115
Initial	1.16	1.16/6	.193
Lifecycle	.983	.983/6	.164

Table 6. Matrix of Paired Comparisons for Preferences of Bridge Materials Under the Bridge Factor (Past Performance) for Wisconsin Counties

	Prestressed Concrete	Steel	Timber	Reinforced Concrete
Prestressed Concrete	1.0	4.9	1.4	.71
Steel	.20	1.0	.56	.24
Timber	.71	1.8	1.0	.56
Reinforced Concrete	1.4	4.1	1.8	1.0

Table 7. Vector of Priorities for Bridge Materials under Past Performance for Wisconsin Counties

	Total of Normalized Row	Vector of Priorities
Prestressed Concrete	1.29	.325
Steel	.35	.089
Timber	.80	.202
Reinforced Concrete	1.55	.384

Table 8. Summary of AHP Models by State and Decision-Making Level

State	Samp. Size	Incon. Ratio	PRE	STL	TMB	REF	PP	LS	MN	RS	IC	LC
All states in study												
State DOT	29	.01	.442	.154	.073	.331	.164	.170	.201	.164	.129	.171
Private Engineers	20	.01	.383	.147	.122	.348	.191	.138	.215	.153	.139	.165
County Engineers	24	.01	.397	.125	.116	.362	.127	.170	.202	.152	.181	.168
Mississippi												
State DOT	5	.05	.527	.150	.048	.275	.123	.194	.218	.160	.170	.135
County Engineers	8	.04	.370	.141	.076	.413	.145	.186	.167	.190	.191	.122
Virginia												
State DOT	12	.01	.333	.204	.090	.374	.171	.153	.266	.157	.093	.160
Private Engineers	7	.03	.326	.263	.145	.266	.239	.115	.262	.112	.082	.190
Washington												
State DOT	4	.03	.496	.134	.069	.301	.184	.149	.166	.144	.163	.194
Private Engineers	7	.04	.466	.128	.080	.326	.134	.119	.231	.212	.126	.178
County Engineers	7	.05	.491	.112	.074	.324	.093	.164	.208	.164	.143	.228
Wisconsin												
State DOT	8	.02	.406	.125	.098	.371	.179	.177	.165	.183	.102	.194
Private Engineers	6	.02	.335	.086	.130	.449	.199	.171	.147	.141	.223	.119
County Commissioners	9	.02	.311	.112	.260	.316	.140	.166	.221	.114	.195	.163

Legend

Incon.Ratio- Inconsistency Ratio
IC-Initial Cost
LS-Life span
LC-Life cycle Cost
MN-Maintenance Requirements

PP-Past Performance
PRE-Prestressed Concrete
REF-Reinforced Concrete
RS-Resistance to Natural Deterioration
STL-Steel
TMB-Timber

Table 9. Statistical Comparisons between Decision-making Groups and States

Kruskal-Wallis Paired Sample or Oneway ANOVA P-Values

Comparison ⇒ / Criteria ⇓	Decision -Groups[1]	States[2]	Decision-Groups within Missis-sippi	Decision-Groups within Virginia	Decision-Groups within Wash-ington	Decision-Groups within Wisconsin
Past performance	.09	.10	.88	.08	.63	.67
Life span	.09	.29	.88	.44	.39	.74
Maintenance	.59	.05	.56	.86	.79	.67
Resistance to natural deterioration	.68	.90	1.0	.61	.63	.27
Initial cost	.60	.23	1.0	.93	.86	.08
Life-cycle cost	.56	.08	.66	.55	.69	.42
Material Preference						
Prestressed concrete	.86	.00	.03	.80	.42	.43
Reinforced concrete	.88	.47	.03	.18	.74	.06
Steel	.01	.00	.24	.20	.80	.08
Timber	.07	.00	.38	.04	.92	.00

1. Comparison between 3 decision-maker groups: state DOT, private engineers, and local officials
2. Comparison between 4 states' decision makers: Mississippi, Virginia, Washington and Wisconsin.

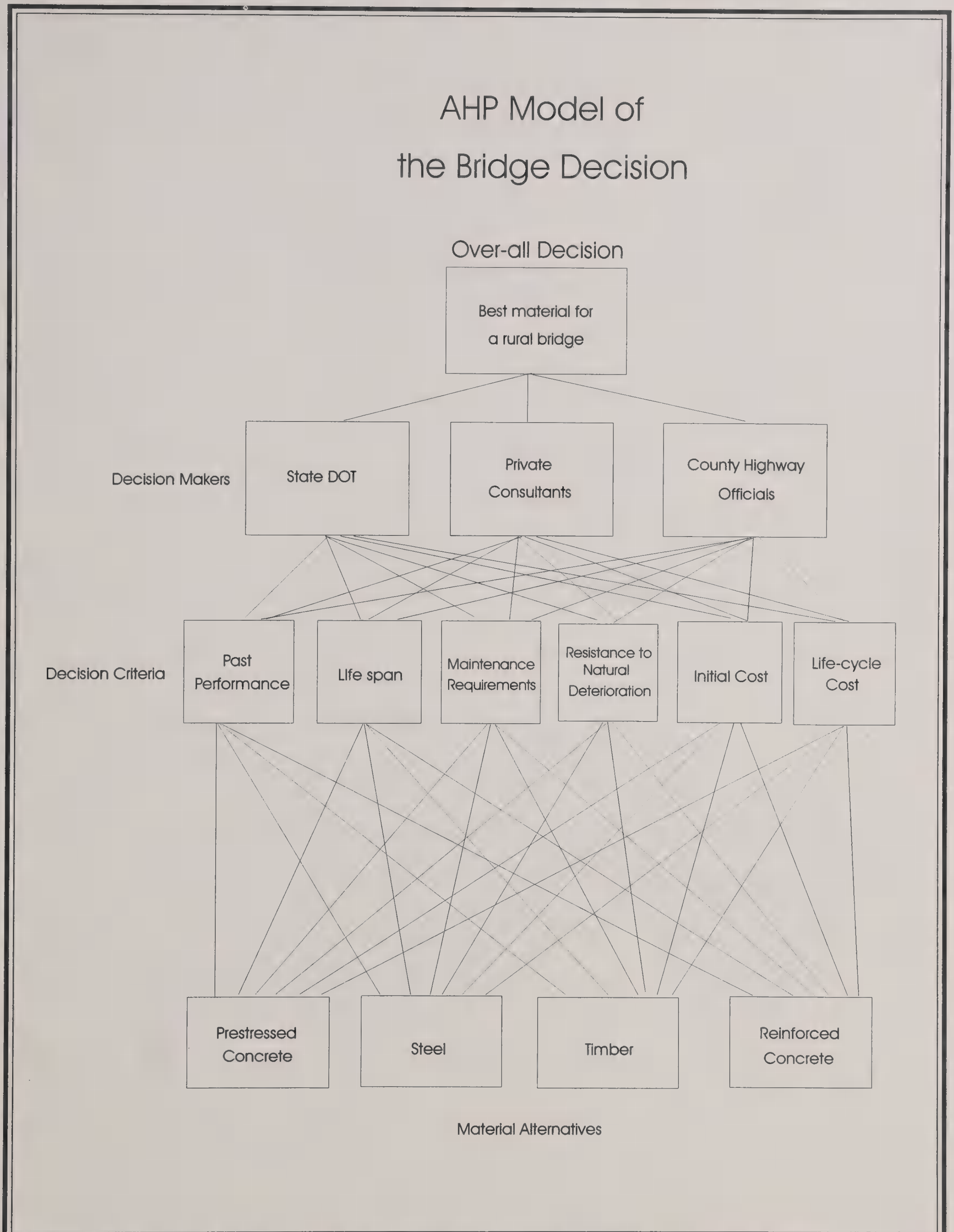


Figure 1. Analytic Hierarchy Model for the Choice of a Bridge Material

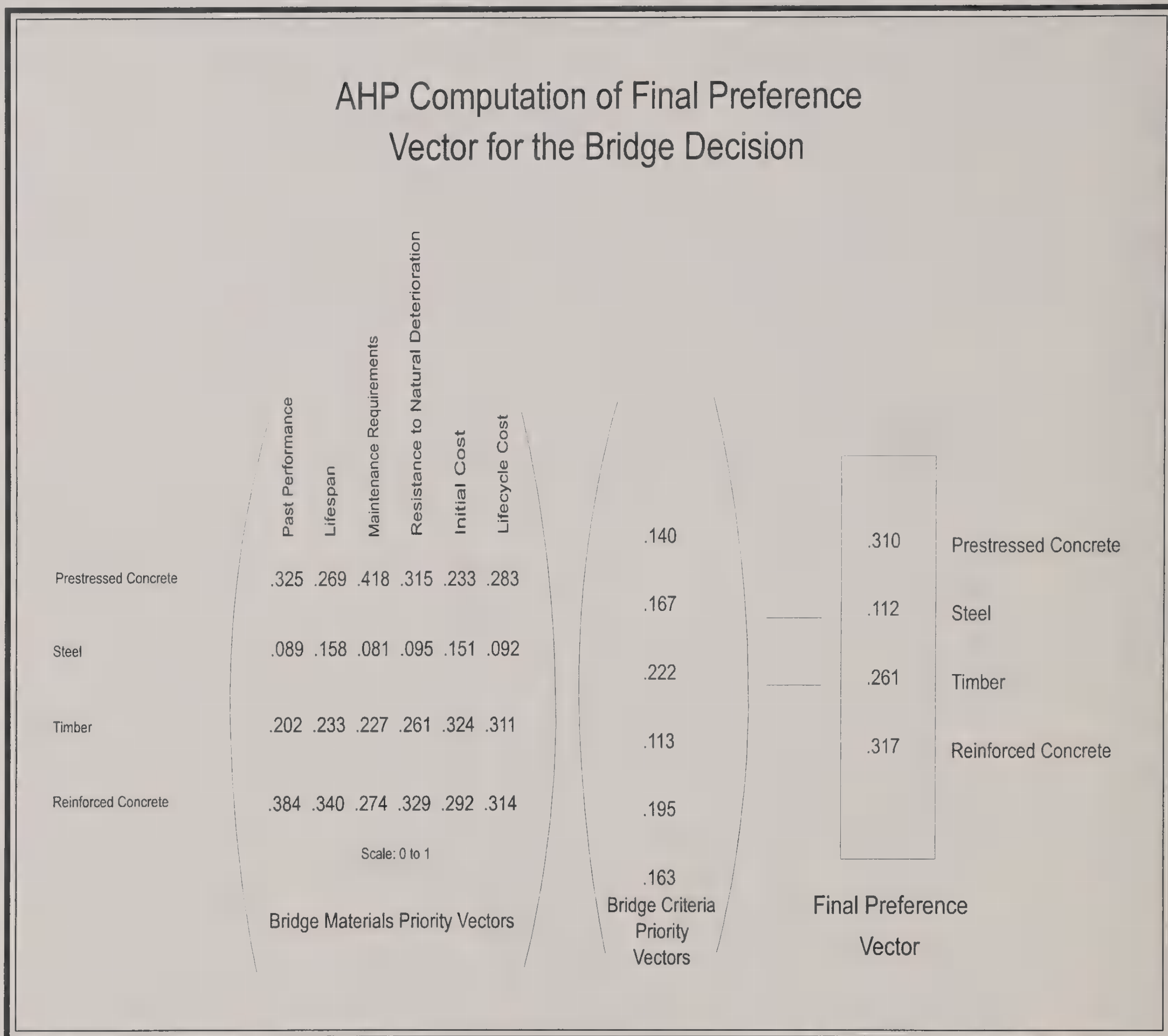
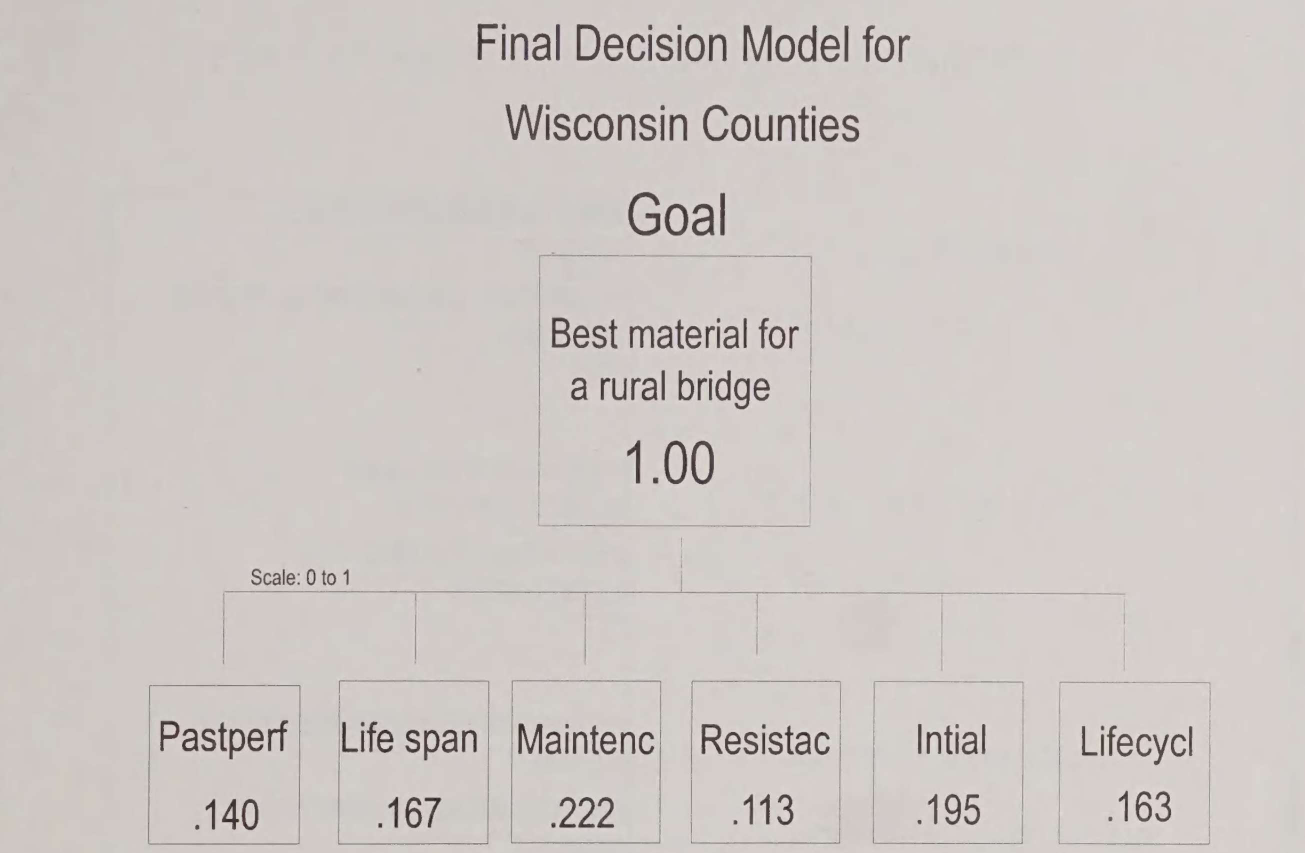


Figure 2. AHP Computation of the Choice of a Bridge Material



	Pastperf	Life span	Maintenc	Resistac	Intial	Lifecycl
Prestress	*.325*	*.269*	*.418*	*.315*	*.233*	*.283*
Steel	*.089*	*.158*	*.081*	*.095*	*.151*	*.092*
Timber	*.202*	*.233*	*.227*	*.261*	*.324*	*.311*
Reinforced	*.384*	*.340*	*.274*	*.329*	*.292*	*.314*

Figure 3. Decision Model for Wisconsin County Decision Makers

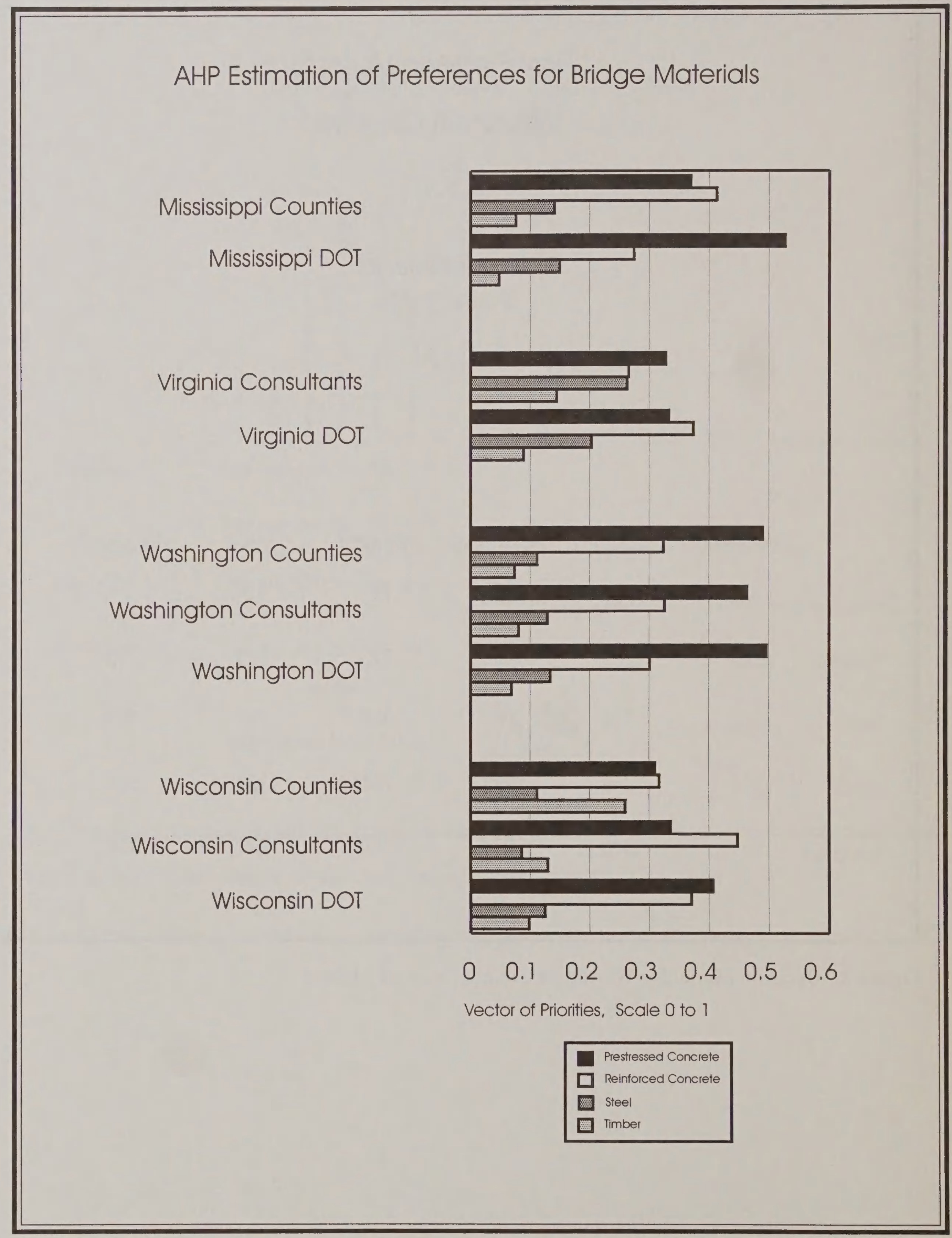


Figure 4. Choice of a Bridge Material by State and Decision Level

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